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LA-UR--83-3704

CONF-8310229--2

DE84 004413

TITLE SOLAR FLARES: AN EXTREMUM OF RECONNECTION

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SUBMITTED TO Presented at the Chapman Conference on Magnetic Reconnection, October 3-7, Los Alamos National Laboratory; Panel Discussion.

December 22, 1983

Los Alamos

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FORM NO 836 R4
ST NO 2629 5/81

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SOLAR FLARES: AN EXTREMUM OF RECONNECTION

by

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I will attempt to emphasize three points.

1. I believe that the solar flare is that particular astrophysical phenomenon that is the extremum of reconnection. No other phenomenon of which I am aware demands as rapid magnetic flux annihilation as is seen in the solar flare.

2. Plasma physics experiments can and should be performed in the laboratory that model reconnection as we observe it in astrophysics.

3. I believe that stochastic field lines derived from something similar to Alfvén wave turbulence are a necessary part of reconnection.

We performed experiments some 20 years ago at Lawrence Livermore Laboratory that gave a hint of what I believe is happening in the rapid reconnection in solar flares.

In this panel discussion Biskamp has just made the point that we need to "break the topology in the third dimension to explain reconnection." The experiments that we performed in the laboratory years ago were ones of mapping the flux surfaces and showed that we had broken just this symmetry; namely, that we no longer maintained a simple cylindrical geometry but had produced a more complicated one. This is similar to what Ed Hones has seen with high-energy particles in the magnetotail.

Solar Flare Topology

Many photographs in optical, EUV, and x-ray wavelengths support the general picture of a twisted loop of flux much like the original picture that Tommy Gold presented for the mechanism of the solar flare. From the magnetic field strength and the density and temperature derived from the emissivity observed in these loops, it is reasonable to infer that the magnetic field configuration is very nearly force free. It is likely that the twisted flux tube or force free field is the basic topology of unstable fields on the sun's surface. However, most modeling of reconnection is done in the limit similar to the Petschek mechanism where the fields are exactly opposite at the reconnection layer, i.e., a neutral point or neutral plane as in the magneto tail. The force free fields of the sun, on the other hand, imply a different topology, namely, one where there is a strong magnetic field in the direction of what would have been called "the ignorable coordinate" or the null surface of the models of opposed field reconnection. The addition of the uniform field throughout the opposed field configuration adds a further constraint to the fluid motions allowable in reconnection as we have just heard reviewed by Biskamp.

Shear and Field Topology

Once a magnetic field is added in the direction of the ignorable coordinate, i.e., the null line, then this becomes a sheared field. The field vector rotates as a function of the distance perpendicular to a flux surface. Most frequently in plasma astrophysics people have called this rotation of the magnetic vector "shear." In cylindrically symmetric geometry, shear leads to a gradient of the pitch. Pitch is defined for an axisymmetric configuration as the reciprocal of the number of turns of a field line per unit length. When the number of turns per unit length is different on each flux surface, then interchanges between two such surfaces is topologically constrained, similar to attempting to "thread" a nut and bolt of different pitch. This topological constraint was originally sought for confinement in thermonuclear fusion plasmas in axisymmetric systems. There are axisymmetric configurations of a helical field of constant pitch where, nevertheless, the field vector rotates as a function of radius. These configurations, "the screw symmetric pinch: are most unstable.

In axisymmetric fusion plasmas one might produce shear, either by internal plasma currents or external winding currents. In the case of coronal loops the option of external rigid current carriers is not available and so one speaks of a force free field with a plasma current that is parallel to the local field vector. This parallel current, $J_{||}$, or field aligned current, as referred to in magnetospheric physics is, I believe, the origin of the instabilities that lead to rapid reconnection. This is because in laboratory plasma experiments the magnitude of this current was correlated with the ease with which the plasma escaped a given configuration. Before discussing the experiment that leads to this belief, I would like to outline some of the reasons for searching for a new and rapid mechanism of reconnection. This motivation is the behavior of the largest and most rapid solar flares.

Conditions of the August 4, 1972 Solar Flare

This flare released some 10^{31} ergs in several 10's of minutes, appeared as a region on the sun of $\sim 2 \times 10^{9}$ cm in major extent and was consistent with a flux tube of this length and radius of $\sim 2 \times 10^{8}$ cm. One assumes that an original magnetic field in this volume of space contained an energy several times greater than that which was released. Some magnetic field remained after the flare. One can then calculate the magnetic field strength such that $B^2/8\pi = 4 \times 10^4$ ergs cm^{-3} and find B of the order of a kilogauss. One can also calculate the inductance of the loop viewed as circuit element 2×10^9 cm long and return current at 2.5 times the original radius or $\cong 5 \times 10^8$ cm. This is 10 henrys only weakly dependent on geometry. The required parallel current of a force free field and this inductance necessary to store the released energy becomes $\cong 4 \times 10^{11}$ amps. This current creates the stress in the magnetic field that is needed to store the released energy. If one interrupts or changes a significant fraction of this current in the characteristic time of the energy release of the flare, namely 1000 s, then the voltage developed along the coronal loop becomes $(d/dt)(LI) = 5 \times 10^9$ volts. If there were a reconnection mechanism that led to a dissipative resistivity that could explain the energy release and hence current interruption of such a flare, then very obviously a fraction of this voltage is available for accelerating the particles that are associated with such a flare. The acceleration of these particles is then a contribution to the resistance.

In particular the hard gamma rays (and neutrons) have been interpreted by Reuven Ramaty and Richard Lingenfelter as requiring the acceleration of 4×10^{33} protons greater than 30 to 50 MeV. If you assume that these protons are accelerated during 10^3 s, then this requires a proton current of 7×10^{11} amps about equal to the current necessary to maintain the stored energy of the force free configuration. Present measurements of gamma rays, as well as x-rays and microwave signals from flares imply that the acceleration of these particles must occur within less than several seconds of time. Such rapid acceleration makes stochastic, Fermi type acceleration mechanisms very difficult under these circumstances, and as a consequence, one is strongly induced to associate the acceleration with the electric fields of reconnection or, that is, current interruption. One is further led to the interpretation that almost all the parallel current has somehow been transferred to runaway protons by a mechanism not yet understood. The impedence presented to the electron flow must become high enough, presumably due to reconnection, to give rise to the necessary resistance or dissipation of the current of the flare.

Comparison of Laboratory Experiments and Solar Magnetic Fields

I wish to compare the mechanism of formation of the magnetic field configuration of a solar flare with the formation of a so-called stabilized pinch in the laboratory. The twisted or helical magnetic field configuration of the stabilized pinch or twisted coronal loop is predominatly an axial field on the inside and an azimuthal field on the outside. It is the same magnetic configuration presumed for solar flares; it is also measured in the laboratory in the case of a stabilized pinch. The difference is only one of time-scales because of the resistive diffusivity due to Coulomb collision processes. In the case of the solar flare, one starts with the emergence of a flux loop and active region. This flux loop may or may not be twisted, and may or may not have a constant number of turns per unit length during the period of emergence of roughly a week. The further twisting of a flux loop can take place because of the Coriolis force induced motions of the large scale eddies that are associated with the "feet" of a flux loop.

During the quiescent presumably stable period of formation, the flux loop emerges from a medium whose pressure is higher than that of the field. After it emer[illegible] the relative vacuum of the corona, the particle pressure is confined by the field stress; that is, the pressure gradient forces are reversed. The diffusion taking place due to resistivity will be relatively modest because the diffusion coefficient corresponding to a resistivity of a plasma at a 10 to 100-eV temperature is relatively small on the space and time scales of a solar flare. For this temperature range the resistive diffusivity is 10^5 to 5×10^3 cm^2 sec^{-1} corresponding to a resistive age for the loop of 10^{11} to 10^{14} s. Consequently, the fluid motions on the time-scale of weeks can be expected to be represented by the perfect conductivity limit. Therefore, "line tied" motions are expected to accurately represent the topological variations observed. The loop of flux can therefore either be twisted further by the hydrodynamic motions of the surface layers of the sun, or the degree of twist may be held constant because no further work is performed by the solar fluid motions.

The Stabilized Pinch or Laboratory Simulation

The laboratory simulation of such a twisted flux tube is performed in an apparatus called a pinch tube. Here, the dimensions are the order of 10 cm diameter so that in order for a plasma to simulate the perfect conductivity limit, the time of formation of the configuration must be less than the time for the fields to diffuse some small fraction of the radius. Typically, one would hope to see the field configuration to be represented by the perfect conductivity approximation for dimensions greater than a centimeter or 20% of the radius. Hence for a diffusion coefficient of 10^5 cm^2 s^{-1}, derived from a plasma temperature of 10 eV typical of these experiments, the time-scale of pinch formation must be less than 10^{-5} s. To form the pinch configuration in this time therefore requires that the voltages used, (d/dt)(LI) must be large, because the field must be large and time of formation small. The magnetic field must be large enough and plasma density low enough such that the Alfvén speed is high enough such that many traversals of Alfvén waves can take place during the pinch formation time.

This is equivalent to the statement that the formation of the field topology must occur quasi-statically. Typical field strengths are then 5000 gauss with particle densities of 10^{15} cm^{-3}. The Alfvén speed becomes 3×10^7 $cm\ s^{-1}$ and hence the traversal time of sound across the diameter is 1/3 μs. Consequently in this approximation, if the pinch were formed in 5 μs, the process would be quasi-static in that there would be some 15 traversals of (magnetic) sound or of Alfvén waves across the system during the formation process.

The voltage required to "drive" this quasi-static formation process can be derived from the inductance, current, and time. A typical length is 40 cm so that the inductance becomes 2×10^{-7} henrys and the current = 5RB, $\cong 10^5$ amps. Consequently the voltage required for the formation of such a configuration in 5 μs is 5 kV. It is because of this voltage and current, (500 MW) that capacitors are used to form the pinch. The capacitor does not "drive" plasma instabilities any more or less than the one-week time scale for the quasi-static emergence and evolution of a solar flare loop. In this case the energy of the flare is largely developed and stored below the solar surface before the flare loop emerges.

Plasma Conditions

The initial laboratory plasma conditions are assumed quiescent in the sense that the resistivity of the laboratory experiment corresponds to a plasma with a temperature of roughly 10 eV. The plasma number density in the case of the laboratory experiment is such that the runaway condition is marginally close to being met. In the case of the solar flare if the topological change due to its emergence occurs in a week, the resistive diffusion layer becomes 1.3×10^4 cm at $kT_e = 100$ eV. This current layer then also meets the runaway condition for an electron density $n \lesssim 10^9$ cm^{-3}.

Hence some local regions of the solar flare should be similar to the laboratory runaway plasma conditions. Therefore, even though a laboratory plasma is "driven" with a capacitor bank it still forms slowly enough to model the quasi-static evolution of a solar flux tube. The microscale phenomenon like plasma oscillations and electron cyclotron periods are so small compared to the formation time that the laboratory and astrophysical circumstances are similar.

Mapping of Magnetic Flux Tubes in a Laboratory Experiment

In Livermore in the early 60's we (Harold Furth and I) were particularly puzzled that the nested sheared flux surfaces predicted by hydromagnetic theory for the stabilized pinch configuration gave such exceedingly poor confinement of a plasma. This poor confinement was inferred from the low electron temperatures even in torodial systems. We therefore felt it was necessary to map the flux surfaces to see whether the topological constraint inferred by shear was somehow or other broken by another phenomenon. Consequently we made a relatively small linear pinch tube, 10 cm in diameter and 40 cm long, and driven by two condenser banks, (1) to form the initial axial field and (2) a second to form the pinch. In addition, an electron beam probe was used to map the flux surfaces by pulsing a short, 10^{-8} s, intense several ampere and high energy 500 kV electron beam parallel to the magnetic field at various radii. The beam was mapped by the fields onto a phosphor and photographed from the opposite end. This is shown in Fig. 1. The mapping of the electron beam at the end plate is essentially an instantaneous mapping of the flux surfaces within the tube. When a rigid copper rod carried the current and the electron beam passed in vacuum, then the flux surface mapped was indeed the sheared magnetic field expected. The original beam circular spot mapped into a short coherent arc. On the other hand when a pinch was formed whose radius was roughly half the original, such that the axial field was compressed roughly fourfold and the external θ-field was correspondingly high, then the simple flux surfaces became stochastic as shown in the later pictures, Fig. 1. These flux surfaces became exceedingly distorted very early in time, namely several microseconds. After several more microseconds in time, half way through the rise of the field, the flux surfaces became totally tangled so that the high energy electron beam was scattered to the wall in less than the full length of the tube. We inferred from these measurements that for reasons then not understood that the magnetic surfaces were being completely destroyed by an unknown instability. We correlated the strength of this instability with the approach to runaway condition of the current carrying electrons. At that time and for many years since we have not understood a mechanism whereby the existence of the tangled field alone would cause energy to be fed into the distortion of the field associated with it stochasticity. It is my strong conviction that such a feedback mechanism most likely exists. If this is so, then the near runaway condition should establish the stochasticity that leads to the loss of the more energetic electrons carrying current of the plasma and hence connect the inside magnetic surfaces with the outside. The loss of these energetic electrons (or energetic ions necessary to maintain charge neutrality) corresponds to a net dissipation of magnetic field energy and hence to reconnection. Such a phenomenon would have a threshold for initiation associated with runaway that in turn may be triggered by a topological change induced by magnetohydrodynamic instabilities. Reconnection should be explored in the laboratory to help to explain it astrophysically.

I am indebted to Albert Petschek for discussions

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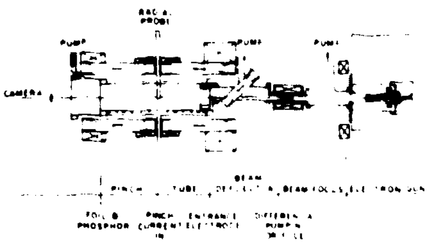

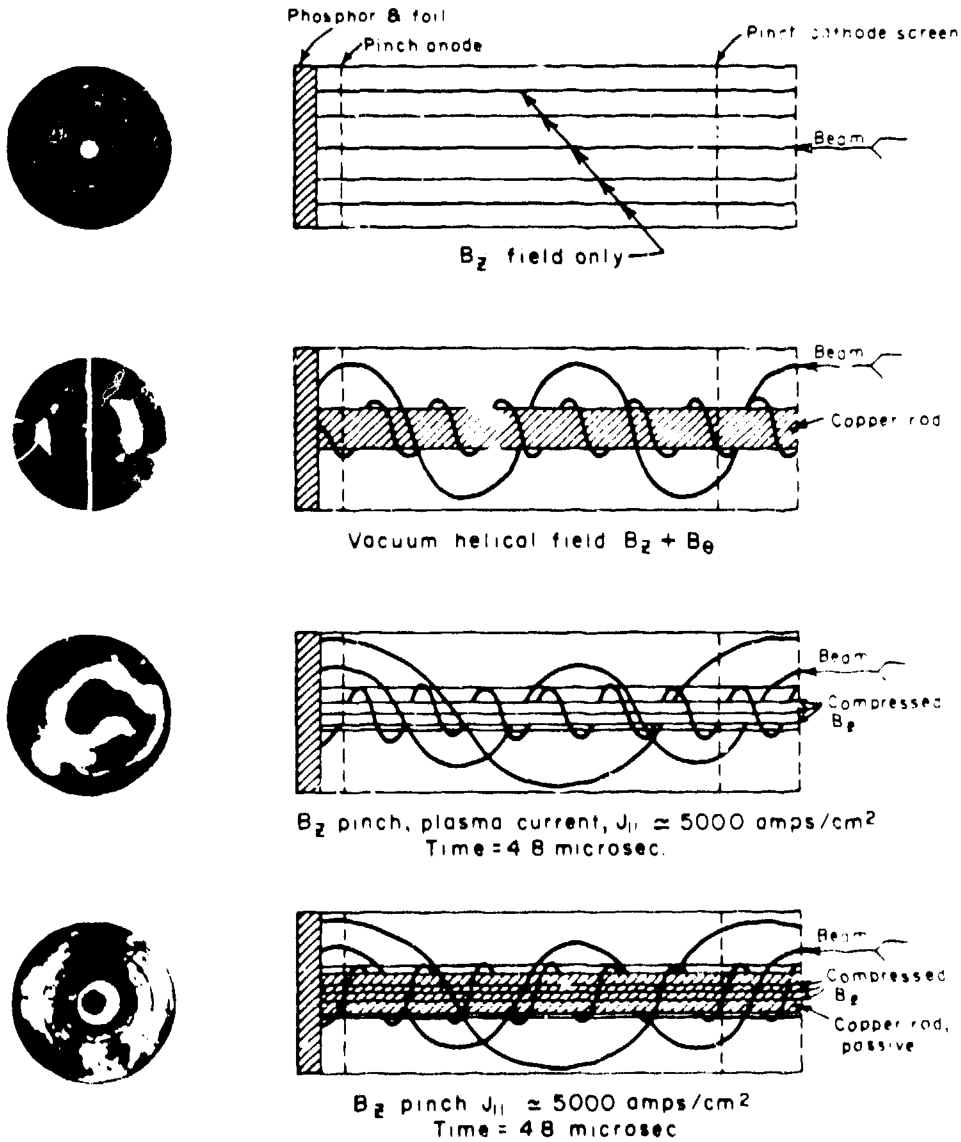

FIG. 2 The linear B_z pinch is probed with a pulsed 0.05 μs, high-energy, 500 keV, electron gun. The aluminum-coated phosphor beyond the pinch anode is photographed, and the beam pattern is displayed in the insert on the left. The vacuum B_z field spot size is small, ~ 1/30 of the diameter (10 cm). When a vacuum B_θ is added by current in the axial copper rod, the shear of the combined fields transforms the spot into an arc corresponding to the different pitch of the adjacent flux surfaces. Two pictures are spliced side by side, one taken with double B_θ showing twice the arc length. When a B_z pinch is made with $B_z \simeq 5000$ gauss and $J \simeq 2500$ A cm^{-2}, the nested-flux surfaces are destroyed and the beam is randomly distributed over the whole pinch. In the bottom picture, current flow in the plasma equals that in the central copper rod. The resulting large shear partially stabilizes the pinch. The beam patterns are the transforms of the tangled magnetic flux. Courtesy of Birdsall *et al.* (1962), and Colgate, S. A., 1978, Ap. J. 221, 1068.